

Different Approaches for Ensuring Performance/Reliability of Plastic Encapsulated Microcircuits (PEMs) in Space Applications

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ABSTRACT

Engineers within the commercial and aerospace industries are using trade-off and risk analysis to aid in reducing spacecraft system cost while increasing performance and maintaining high reliability. In many cases, Commercial Off-The-Shelf (COTS) components, which include Plastic Encapsulated Microcircuits (PEMs), are candidate packaging technologies for spacecrafts due to their lower cost, lower weight and enhanced functionality. Establishing and implementing a parts program that effectively and reliably makes use of these potentially less reliable, but state-of-the-art devices, has become a significant portion of the job for the parts engineer.

Assembling a reliable high performance electronic system, which includes COTS components, requires that the end user assume a risk. To minimize the risk involved, companies have developed methodologies by which they use accelerated stress testing to assess the product and reduce the risk involved to the total system. Currently, there are no industry standard procedures for accomplishing this risk mitigation. This paper will present the approaches for reducing the risk of using PEMs devices in space flight systems as developed by two independent Laboratories. The JPL procedure involves primarily a tailored screening with accelerated stress philosophy while the APL procedure is primarily a lot qualification procedure. Both Laboratories successfully have reduced the risk of using the particular devices for their respective systems and mission requirements.

INTRODUCTION

PEMs are much more readily available than hermetic devices, mainly because market forces (cost and volume) encourage most designs to be developed first as plastic-encapsulated [1,2]. At any given time, more part functions are available in plastic than in ceramic [3]. The U.S. military and government, the major purchasers of hermetic parts, have become relatively small portions of the total electronics market. It is estimated that hermetic parts will account for less than 0.25% by the year 2000 [4]. With package technology moving to surface mount, development of ceramic packages has lagged further in the microelectronic market, making adaptation of plastic-packaged integrated circuits to government and military applications even more critical. With global competition, industrial research in materials and manufacturing processes will continue to focus on PEMs. The cost of a packaged electronic part is determined by several factors: die, package, volume, size, functional complexity, assembly cost, screening yield, and the specified qualification-required tests. In general,

PEMs weigh about half as much as ceramic packages [3]. A lighter package results in a smaller overall payload for the same board functionality, a concern of critical importance for space missions because the payload size dictates the launch vehicle requirements.

Hermetic packages usually have a higher material cost and are fabricated with more labor intensive, manual, processes due to smaller volume requirements. In addition, hermetically packaged integrated circuits purchased to military specifications can have material costs up to ten times more than plastic packaged integrated circuits because of the rigorous testing and screening included in the procurement costs [5]. When both types were screened to customer requirements, it is estimated that purchased components for plastic packaging of integrated circuits cost 12% less than their hermetic counterparts, primarily due to the economics of high volume production [6]. One of the issues facing the space industry is that most PEMs are not screened by the manufacturer to their equivalent hermetic counterpart (if one exists). Therefore, users must screen and qualify PEMs for each of their applications.

Qualification tests estimate expected life and design integrity of a device. They are destructive by nature. Most tests are not conducted at the application conditions, but incorporate accelerated levels of stress to accelerate failure mechanisms, often at known sites in a device. The main purpose of qualification and/or screening of any component is to mitigate risk to the end user.

Many of the new NASA missions follow the "faster, better, cheaper" philosophy which is intended to mitigate as much risk as prudently possible for a reasonable cost. The reliability assessments presented in this paper show solutions for a moderately long mission with moderate budgetary constraints and a relatively short mission with tight time and budgetary constraints. There are common elements and concerns for both approaches which is able to reduce risk to the respective programs.

RELIABILITY OF PEMs

The reliability of plastic-encapsulated microelectronics has increased tremendously since the 1970s, due largely to improved encapsulating materials, die passivation, and manufacturing processes. In particular, modern encapsulating materials have low ionic impurities, good adhesion to other packaging materials, a high glass transition temperature, high thermal conductivity, and coefficients of thermal expansion matched to the leadframe. Advances in passivation include fewer pinholes or cracks, low ionic impurity, low moisture

absorption, and thermal properties well matched to the substrate.

The forces driving these improvements are the system manufacturers that have placed increasingly stringent quality and reliability requirements on PEM suppliers. At the start of 1995, an Average Outgoing Quality factor of less than 20 ppm and failure rates of less than 10 FIT (Failures in Time) were not uncommon. It is expected that these numbers will decrease by an order of magnitude by the end of the decade [7].

The best endorsement for PEMs is from automotive manufacturers. For example, automotive qualification includes sample temperature cycling for 1000 cycles, thermal shock (liquid-to-liquid) for 500 cycles, 85°C and 85%RH testing for 1000 hr, life testing for 1000 hr, high-temperature reverse bias for 1000 hr, intermittent operational life testing for 20,000 cycles, and autoclave (live steam) testing for 96 hr. The number of rejects allowed for all these tests is zero. Most vendors pass these tests without problems, indicating a broad, industry-wide ability to meet or exceed harsh automotive standards [8].

ISSUES WITH USING PEMs

Even with modern improvements to PEMs reliability there are still uncertainties associated with using PEMs in space environments. Some missions require the electronics to operate in a relatively benign environment while other missions are more severe. At this time, most companies including APL and JPL are taking a conservative approach to the use and qualification of PEMs for space.

Currently, user's of electronics for space applications screen and derate all parts, plastic or hermetic, for each application. When high-rel hermetic packages are procured, the manufacturer has generally screened them (with the cost passed on to the end user). This is not the case for PEMs. The end user must decide on how best to screen and/or qualify parts for their particular application. Sometimes the screening is intended to assure that parts can be used outside of the manufacturer's specified limits. The University of Maryland CALCE Center has termed the process to use parts in this manner as 'uprating' [9].

The choice to *uprate* can come with various legal consequences. Most manufacturers have advocated that using a part outside its intended temperature range will automatically invalidate any implied warranty. At this time, APL does not plan to use COTS or PEMs outside of the manufacturer's recommended use conditions during flight operation. These conditions are exceeded, however, during system ground base testing. APL has developed a screening and qualification methodology to assure long-term device reliability and integrity are not compromised. JPL is currently using PEMs outside of the recommended range, primarily on the cold side of the specification, for missions to Mars. The process developed at JPL to assure parts can reliably meet mission temperatures has been called 'upscreening'. Both Laboratory strategies are subject to change for future missions based on results of future data.

MITIGATING THE RISKS OF USING PEMs IN SPACE Suggested Mitigating Techniques (used by APL and JPL)

Not all manufacturers and assemblers of PEMs are the same: they use different encapsulants, additives, lead-frames, die passivation materials, assembly processes, and materials. Manufacturers of PEMs must implement qualification

procedures tailored to evaluate and monitor the capability of their product to meet desired service life in the expected applications to assure that products made with PEMs are reliable. Unfortunately, the space environment is not one of the intended applications currently targeted by manufacturers for PEMs. As such, PEMs intended for space applications typically require additional screening and/or qualification testing to be performed by the user. The purpose of this testing is to compliment what the manufacturer has already accomplished.

The Screening Process

The terminology "screening" traditionally implies 100% verification testing at the piece-part level. Complimentary sample-based tests such as mechanical inspection may be performed, as well.

While differences exist, both companies agree that a common baseline includes electrical verification at the mission temperature profile, radiographic inspection, and visual & mechanical inspection.

Appendix A provides a detailed description of each screening stress and the reasons for using the stress. Actual test results are presented under the "Approaches to Using PEMs in Space" section.

The Qualification Process

Objectives of qualification testing can be to evaluate the effectiveness of new materials, processes, and design; to supply routine information on the quality of a product; to develop information on the integrity of a device and its structure; and to estimate its expected service life. Qualification tests are destructive by nature. Most tests are not conducted at the application conditions, but incorporate accelerated levels of stress to accelerate failure mechanisms, often at known sites in a device [10].

Unlike the device manufacturer who must balance device reliability and product yield, the space-user is strictly concerned with assuring device survival during integration, test, launch, operation, and (if necessary) storage. In application conditions where the environment is not controlled, the load profiles of temperature, humidity, vibration, contamination, and radiation, as a function of time, must be predicted based on past experience. Past experience for space applications is not always available. Currently, many companies are building a database to record such data.

Appendix B provides a detailed description of each qualification stress and the reasons for using the stress. Actual test results are presented under the "Approaches to Using PEMs in Space" section.

The Derating Process

The derating process is a prudent practice to follow, whether or not a device has a military or commercial pedigree. As previously stated, it involves reducing device voltage, current and power by a certain percentage to extend longevity.

In APL's case, it was determined that the upper temperature boundary for PEMs (e.g., +70°C or +85°C) necessitated a change to existing derating guidelines used for microcircuits. APL had determined that the derating factors could be adhered to provided the allowable temperature limit for junction temperature (T_j) was extended. Worst-case, this meant changing the upper limit for T_j from +100°C to +110°C. The +110°C figure is still well below the typical manufacturer's

rating of +175°C (or higher). JPL utilizes an internal laboratory specification that uses +110°C, as such no changes in policy were required.

APPROACHES TO USING PEMs IN SPACE

Building high reliability spacecraft at APL & JPL used to be a relatively straight forward process that involved the selection, purchase, and use of military qualified Class 'S' and/or Class 'B' parts for all of the components. The spacecraft was built according to customer dictated requirements.

Historically, the customer would expend considerable resources (e.g., time and money) being personally involved in the manufacturer's design process and overall program management. In today's "faster, better, cheaper" paradigm the space customer outlines the mission requirements and holds the manufacturer responsible for meeting the requirements. The only degree of customer oversight is in the area of cost and schedule. The attractiveness and increased use of COTS and PEMs are a direct response toward attempting to meet these constraints.

Most manufacturers of space flight hardware have very conservative manufacturing practices. When using new packaging technologies, such as PEMs, even more conservatism is warranted. The approaches presented below were developed and used by APL and JPL. It is important to note that they are not *set in stone*, but rather, serve as a guideline on which to build. It is entirely possible that future missions may utilize a different testing methodology.

Before going into program specifics, the authors would like to highlight some key points of the methodologies described.

One major difference between the approaches regards burn-in. JPL performs burn-in as part of their screening process, with parts being tested at maximum operating conditions. APL prefers to test parts at +125°C, on a sample basis, as part of their qualification process.

Another outstanding difference has to do with how each Laboratory handled C-mode Scanning Acoustic Microscopy (C-SAM) results. Both agree that acoustic microscopy is a powerful tool and that there are numerous references which cite the importance of C-SAM in assessing the reliability of PEMs [11]. However, there does not exist today an industry standard for assessing the acceptance or rejection of PEMs based upon C-SAM results. It is for that reason APL and JPL did not use the same criteria for selecting parts for the programs shown in this paper. JPL chose to use C-SAM results as a screening tool. They discarded parts that exhibited delamination. APL assumes delamination will be present in all PEMs. Mitigation of possible failure modes is therefore accomplished by conformally coating printed circuit board containing PEMs.

An extremely positive outcome has been the agreement on the need for the development of new standards regarding the interpretation of Destructive Physical Analysis (DPA) results of commercial devices. Data, from both Laboratories, revealed that the majority of microcircuit devices analyzed were found to be deficient in meeting the governing military specification requirement of 50% for step-coverage. While the military document does have an acceptance criteria for coverage as low as 30%, this number is still well above the typical design rules applied by most commercial manufacturers.

Finally, both Laboratories want to emphasize that independent of the PEM issue, radiation effects are a crucial

concern for space applications. However, since this is not strictly a PEM related topic, testing results are not presented in this paper. Appendix B describes the test conditions only.

The JPL Approach – MARS01 Pancam

The Qualification story that follows was designed as a 'Tailored Screen' for the Mars01 Program. The Mars01 Program had a system board that required the use of 3 PEM devices. This program is one of the "better, faster, cheaper" NASA programs. There were numerous monetary and time constraints on the screen/qualification of the PEMs used in this program. Below is an outline summary of some of the constraints placed on the program.

MARS01 Pancam Requirements

- Mission life < 1 year (1500 hours operating)
- Operating temperature (day only) = -50°C to +10°C
- Number of T/C ~ 365
- No assembly board burn-in planned
- Outgassing is a concern (optics)
- Environmental moisture is not a concern

As can be seen, this mission is very short, less than one year, and needed only survive approximately 365 temperature cycles (one per day during the 1 year). The program was convinced that a PEM Amplifier, A-to-D converter and a DC-DC Converter was merited due to the PEM version being the state-of-the-art for those technologies. In addition to the above constraints placed on the qualification, there were serious time and monetary constraints.

The two constraints listed above precluded the traditional qualification procedure and suggested that a different approach be employed in order to mitigate as much risk as possible to the program. A process flow was developed which was tailored to minimize the qualification time and cost while also minimizing the risk to the Mars01 program. The flow is depicted below in Figure 1.

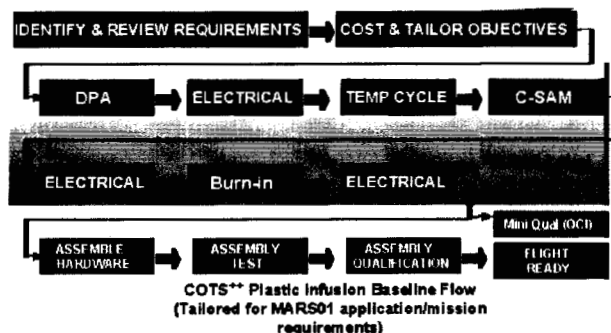


Figure 1. Tailored Screen Flow for PEMs for the Mars01 Program. Notice that this flow is Primarily a Screen with a Mini-Qualification.

For this tailored approach, small lots of each of the three device types were purchased and 78 devices were entered into the flow (for each device type) following a DPA. The DPA and screening results are shown below in Table 1. All devices passed examination, however there was one marginal metallization pass from the ADC vendor. As mentioned earlier, commercial die are not fabricated to the same design rules as

class S and military grade devices. This will require engineering judgement every time a PEM is considered for use on a Hi-Rel mission.

Table 1. DPA and Screening Results (No. Of Rejects)

Vendor A Amplifier	Vendor B ADC	Vendor C DC-DC Converter
External Visual – 0	External Visual – 0	External Visual – 0
X-Ray – 0	X-Ray – 0	X-Ray – 0
Internal visual – 0	Internal visual – 0	Internal visual – 0
SEM – Pass (0/4)	SEM – (1/8) ⁽¹⁾	SEM – (0/4)




(1) Voids found in the sidewall metallization at contact windows and were observed to be thin for one part. Although all parts were of the same date code, the dice were clearly from different processing lots.

Note: Reject criteria were defined by JPL to be a potential risk to mission success.

Following the initial screening (above) all of the parts were electrically tested to the manufacturer's data sheet. There was a failure of one of the DC-DC converters at -55°C (failed parametric). It is considered important to test any PEM to the full data sheet for space applications, particularly if the end use is near the extreme of the manufacturer's specification.

At this point, all devices were subjected to temperature cycling from -60C to +25C for 10 cycles. The purpose of the temperature cycling is to stress the package similar to the conditions the electronics will see in service. Following the stress of temperature cycling all packages were examined by the use of acoustic microscopy (in this case C-mode scanning acoustic microscopy – CSAM and through mode were used) to inspect for delamination of the plastic to the die surface and to the leadframe material and others. There is evidence that delamination at these surfaces can be a reliability concern [11]. The results for CSAM was that there were significant amounts of delamination found in two of three device types. Vendor A did not exhibit significant amounts of delamination. At this point in the screen, it was decided to discard the packages that exhibited >75% delamination from die edge to package edge and >25% delamination of any front or backside die area. The C-SAM results are tabulated in Table 2. A significant number of devices were lost at the C-SAM step but the procedure is designed to pick the devices with the very best chance to satisfy the Mars01 requirements.

Table 2. C-SAM Results Following Temperature Cycling

Amplifier - Vendor A	ADC - Vendor B	DC-DC Converter - Vendor C
Top Side: 0/78 ⁽¹⁾	Top Side: 30/78	Top Side: 0/78
Back Side: 3/78	Back Side: 8/78	Thru Scan: 16/78
Typical Rejects:		
		
Pass	Fail	Fail

Note: Units with delamination are defective and were defined by JPL to be a potential risk to mission success. (1) All units showed 100% delamination caused by a special die top coating. These parts were not rejected. F.A. confirmed a die top coating. This was validated by the supplier.

The next step in the flow was for electrical testing to be performed to identify any fallout due to the temperature cycling stress and to "weed-out" any failures before burn-in. These results are shown in Table 3. There was some fallout

experienced from vendors B and C. These devices dropped out early in the screening flow. Obviously, if they were not screened out and procured for the mission, there would have been a failure on the mission.

Table 3. Electrical Test Results (Pre Burn-in – No. Of Rejects)

Electrical Test Temp.	Vendor A Amplifier	Vendor B ADC	Vendor C DC-DC Converter
+25°C	0	10 ¹	2 ¹
+55°C	0	0	1 ¹

(1) Failures included are parametric and functional

The devices were then burned-in and electrically tested again. The burn-in chosen for this was for 100% of the devices to receive a burn-in that simulated the use conditions and also simulated the length of the mission (1500 hours). The burn-in was dynamic for 72 hours at 55°C at maximum rated Vdd (this condition was calculated to simulate 1500 hours at -10 °C by using a temperature acceleration factor of 21 and an activation energy of .33eV). The result of the burn-in is tabulated in Table 4. There were 3 cold failures for Vendor B. Since this particular mission requires service at cold temperatures, this portion of the screen again culled devices that could have failed during the mission.

Table 4. Post burn-in Electrical Test Results

Electrical Test Temp.	Vendor A Amplifier	Vendor B ADC	Vendor C DC-DC Converter
+25°C	0	0	0
-55°C	0	3 ¹	0

¹ Failures included are parametric and functional

The tailored screen at this point is considered finished and the devices can be assembled onto the flight hardware. One final check was designed to verify that the screen was adequate to eliminate the weak devices and there was enough life left to be reliable during the Mars01 mission. The method used was to take a sample of devices (that went through the above flow) and perform an additional burn-in on them (these devices are not intended to be used on the mission). The ideal result would be that all of the samples pass 100% indicating that the screen was successful at eliminating the weak devices and still left enough life for the mission. The results tabulated in Table 5 strongly suggest that the upscreen flow was a success.

Table 5. Electrical Test Results Following the Screen – No. Of Rejects

Electrical Test Temp.	Vendor A Amplifier	Vendor B ADC	Vendor C DC-DC Converter
+25°C	0/10	0/10	0/10
-55°C	0/10	0/10	0/10

The APL Approaches – APEX and TIMED

APL has currently developed two different methodologies that can be used for screening and qualifying PEMs for space applications. These two approaches cover two possible mission extremes. The first approach to be described will be for the APEX Program, a short-duration sub-orbital mission. The other, will be a more extensive approach, currently being developed and utilized on the TIMED mission.

APEX MISSION

- Mission Life: 17 Minutes Operating (Launched: Jan. 22, 1999)
- Development Cycle: 6 Months (Design to Delivery)
- Operating Temperature = 0°C to +25°C
- Environmental Stress Screening at Board Level in Lieu of Piece-Part Screening
- Outgassing, Moisture, and Radiation Not a Concern

As can be seen, this mission had a very short development and mission operation requirement. Due to the serious time and monetary constraints placed upon the program, a radical new approach to design and quality assurance needed to be implemented. In accomplishing these goals the cognizant design engineers requested and were empowered to:

- Make Extensive Use of COTS and PEMs
- Purchase Parts Directly
- Utilize a Rapid Design Change Process (Design & System Engineer Signature Only)
- Maintain Responsibility for Configuration Control
- Utilize an Integrated Process Team Assigned For Fabrication

The shift in responsibility for the majority of quality assurance functions to the design engineering staff was certainly a radical departure from traditional APL norms.

In efforts to mitigate any potential risk to the Program, it was concurrently decided to perform Environmental Stress Screening (ESS) at the board level. ESS is a process in which a populated printed circuit board is subjected to temperature cycling in a powered state. The intent of ESS is to cull any potential gross workmanship defects that may exist as a result of the fabrication (and to a limited extent design) process.

Upon completion of the ESS testing, a visual inspection by a quality assurance engineer was performed. Feedback from this inspection was given to the design engineer. The design engineer then determined if any changes were required.

In addition to ESS of the boards, vibration and electrical verification tests were performed at box and system level. Temperature cycling at box level and spin-balance at system level were also conducted.

As a final footnote, APEX was successfully launched on January 22, 1999. Preliminary data indicates that all mission goals were met or exceeded.

In stark contrast to the APEX mission is the TIMED mission. APEX involved the design and delivery of 2 instruments to NASA/Wallops for launch of a 17-minute sub-orbital rocket. TIMED, on the other-hand, is representative of the traditional 2-5 year operational spacecraft developed by APL. APL's responsibility extends from inception through post-satellite tracking and communication.

TIMED MISSION

- Mission Life: 2 Years Operating (Launch: January 2000)
- Development Cycle: 3 Years (Design to Launch)
- Ground-Based Test Temperature = -40°C to +100°C
- PEMs On-Orbit Operating Temperature = 0°C to +50°C
- Outgassing, Moisture, and Radiation All Concerns

From the information above, it can be seen that ground-based testing presents the most hostile environment for PEMs used on TIMED. The lower test temperature limit of -40°C

exceeds the manufacturer's rating of 0°C for 3 of the 15 PEMs used. The upper test temperature limit of +100°C exceeds the manufacturer's upper temperature rating for all devices. Once in orbit, however, the part temperature falls well within the manufacturer's maximum absolute ratings (e.g., 0°C to +50°C).

In order to mitigate any concerns associated with the ground based testing APL has developed and utilized the following screening and qualification flow:

TIMED SCREENING

- Visual & Mechanical Inspection
- Electrical Verification at Mission Temperature Extremes
- Real-Time Radiographic (X-ray) Inspection

TIMED QUALIFICATION

- Radiation Hardness Assurance (not covered in this paper)
- Temperature Cycling (T/C)
- Steady-State Temperature Humidity Bias Life (85/85)
- Destructive Physical Analysis (Including C-SAM)
- High Temperature Operating Life (HTOL)

To give the reader more insight, results of PEM testing have been grouped into 3 categories: Integrated Circuits, Resistor Networks, and Transistors. The breakdown, by category, is shown in Table 6.

Table 6. TIMED Part Breakdown

Integrated Circuits	Resistor Networks	Transistors
7 Device Types	7 Device Types	1 Device Type
5 Manufacturers	1 Manufacturer	1 Manufacturer
10 Line Items	13 Line Items	2 Line Items

Due to the number of vendors and part quantities involved, data in Tables 7 and 8 will be presented in terms of quantity failed per total quantity tested.

Table 7 details the results encountered for screening. It is suspected that the electrical fallout of the resistor networks at cold temperature is not entirely accurate. During the qualification process it was determined that the tester accuracy could result in false failure being recorded. Though devices were never actually retested, the 2.4% failure rate (at +25°C) is considered to be more representative of the actual device failure rate.

Table 7. TIMED Screening Results

Test	Integrated Circuits	Resistor Networks	Transistors
	(# Fail / # Tested)	(# Fail / # Tested)	(# Fail / # Tested)
Electrical @-40°C	0 / 828 ¹	87 / 1520	0 / 157
Electrical @+25°C	4 / 828 ¹	36 / 1520	0 / 157
Electrical @+100°C	0 / 828 ¹	36 / 1520	0 / 157
X-Ray	5 / 593	18 / 977	0 / 157
Final Visual	7 / 754	3 / 2375	3 / 378

¹ Four failures at +25°C are parametric in nature and are attributable to a single part lot of 188 devices. These devices were functional at all temperatures. Fixture limitations prevented this lot from being tested parametrically at -40°C and +100°C.

Table 8 details the results for qualification, to date. Three outstanding DPA reports and 1 failure analysis are yet to be completed. In addition, life test on 1 microcircuit is yet to begin. As with the screening data, above, some explanation is required regarding the test results. Note: For HTOL, data is subdivided into post-electrical measurements at the specified temperature.

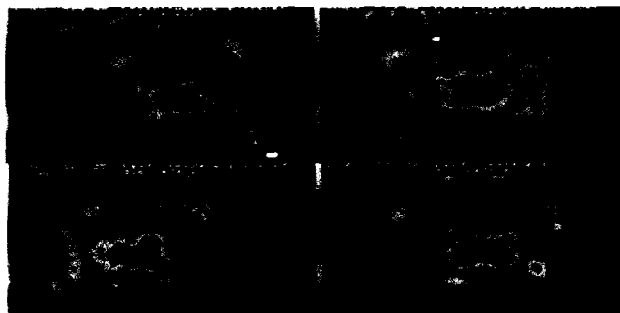
Table 8. TIMED Qualification Results

Test	Integrated Circuits (# Fail / # Tested)	Resistor Networks (# Fail / # Tested)	Transistors (# Fail / # Tested)
T/C	2 / 60	0 / 32	N/A
85/85	1 / 30	N/A	N/A
DPA	9 / 20	0 / 35	3 / 3
HTOL Electrical @-40°C	0 / 110	0 / 44	1 / 22
HTOL Electrical @+25°C	0 / 110	0 / 44	0 / 22
HTOL Electrical @+100°C	3 / 110	2 / 44	1 / 22

In interpreting the results, let us start with the high failure rates for DPA. In all instances the rejection was a direct result of not meeting the criteria for metallization step-coverage as already discussed. It is important to note that all devices labeled as failing, successfully completed life testing for 1000 hours at +125°C.

As part of every DPA on PEMs, C-SAM is performed. The C-SAM results are used for informational purposes, not as cause for lot rejection. One device however, reference Figure 2, was considered to have questionable construction. According to the report "Every part had at least one lead-frame element that appeared to be 100% delaminated on the top-side; four parts had a similar delamination on the bottom-side." The report goes on further to state "This is a reliability concern due to the possibility of contamination encroachment." As already stated, APL assumes this condition exists in all product and therefore uses conformal coating as a mitigation technique.

Figure 2. C-SAM Results From DPA



Next, let us discuss the justification for acceptance of life test failures. As can be seen from Table 8, all three categories of devices had suspect life test failures after post-HTOL +100°C electrical measurements. In addition, for the transistor grouping, a possible failure was detected as a result of post-HTOL -40°C electrical testing.

In the case for the integrated circuit grouping, the three failures identified are all attributable to a single part lot. Furthermore, only a single parameter was in question. Review of the pre-test data revealed that the parts were at the high end of the manufacturer's specified limit (36mA). Actual post-data

values recorded were just slightly over the required value, measuring 36.3mA, 36.4mA, and 37.4mA, respectively. Since the failures could be considered as marginal, at best, with a worst-case delta measurement of 8.9%, it was decided to accept the devices "As-Is."

As with the integrated circuit grouping, the two failures identified in the resistor grouping were attributable to a single part lot and a single questionable parameter. The two parts in question measured outside the manufacturer's specified resistance value by 0.3% when tested at post-HTOL +100°C. Detailed review of the test set-up revealed that the accuracy of the equipment could result in a false reading. Specifically, as little as a 2:A shift in current could produce a 40Ω change in resistance. Furthermore, the failures occurred at a temperature in excess of the manufacturer's rating of +70°C. It was decided to accept the devices "As-Is" after a second lot of resistors (different value) successfully passed life testing.

As with both previous groupings, the transistor failures were attributable to a single part lot. However, in this instance, one device failed a particular parameter at post-HTOL -40°C electrical measurements. A separate device failed a completely different parameter at post-HTOL +100°C measurements. The challenge for this device was the fact that the manufacturer only specified +25°C electrical test limits in their data sheet. Consultation with vendor resulted in no additional information. As such, the justification for use resided with the design engineer. The cognizant engineer was contacted and it was decided that the parts were acceptable for the application. Note: Whenever acceptance is limited to a specific application, a Program waiver is required. A new waiver is necessary for use on any future application (even on the same spacecraft).

The last two failures documented on Table 8 have to do with Temperature Cycling (T/C) and Steady-State Temperature Humidity Bias Life (85/85) testing. Little can be said on the 85/85 failure, since the failure analysis of this device is still in process. However, this much is known: The failure was attributable to a single part lot. All devices had successfully completed post-85/85 electrical measurements at 50 and 100 hours. At the 200-hour interval (the total time required for the test), one device ceased to function electrically. The test set-up and program were verified to be correct and visually inspection of the part revealed no anomalous conditions. A retest confirmed the failure. The part was then subjected to a bake-out (24 hours at +125°C) to eliminate any potential moisture related concerns. The failure remained after post-bake retest. At this point, a legitimate failure was suspected and the device was sent to the failure analysis lab. Though a final decision has not been reached on this part lot, it is important to mention that the 200 hours limit is based upon conservative factors which, when compared against the mission constraints, constitute in excess of four times margin. Just passing the 100 hours mark provides a greater than two times margin.

Finally, the disposition of the T/C failures needs to be addressed. The T/C failure was attributable to a single part lot. Two different devices ceased to function electrically after completion of the 20 required cycles. The test set-up and program were verified to be correct. The part was then subjected to a bake-out (24 hours at +125°C) to eliminate any potential moisture related concerns. The failure remained after post-bake retest. Visual inspection of the test board indicated possible poor contact between the part and the board. In order to confirm this suspicion, the Uralane coating needed to be

removed. Continuity check after coating removal revealed that several leads, on both devices, were not adequately soldered to the test board. The leads were re-soldered to the board and both devices functioned normally. Since the failure mode was a attributable to workmanship and not performance, the devices were accepted "As-Is." In essence, the T/C test fulfilled one of its intended purposes, the detection of improper solder joints.

SUMMARY

COTS devices, including PEMs, have found their way into spacecraft designs and the trend is likely to continue. Advantages of plastic packages over their ceramic counterparts include lighter weight, enhanced functionality, including access to state-of-the-art technology, and increased product availability. Lower operational temperature profiles have been the only significant detriment toward greater acceptance of these devices by the space community.

Developing a successful and reliable mitigation strategy is the challenge facing the space user that wants to take advantage of the benefits PEMs can provide. This paper has illustrated three distinct types of missions, ranging from lifetimes of 17 minutes to 2 years, and solutions to mitigate risk for each. It is clear from this work that each space mission is unique and that a universal solution for mitigating risk does not exist. Screenings and qualifications must be tailored to specific mission requirements.

Where missions in the past were well specified and utilized Hi-Rel parts, new missions require creative solutions for upscreening and qualifying COTS and PEMs. As always, APL and JPL proceeded with conservative approaches, weighing risk against mission requirements. As space hardware manufacturers become more knowledgeable with using PEMs, other screening and qualification methods will be developed. APL and JPL are planning to use PEMs in future missions and will continue to develop upscreening and qualification plans tailored for their respective programs.

APPENDIX A – SCREENING TESTS

Electrical Verification

Most PEMs do not meet standard military temperature range (i.e., -55°C to +125°C). This should not be viewed as an immediate cause for concern, but a risk to be mitigated. What is most important is for the PEM in question to meet the appropriate mission temperature profile. In most instances the most severe temperature extremes occur during ground based testing, not during actual flight. However, if no alternative part can serve, it becomes necessary to assure that part can function at the temperature profile required. To assure a part will function reliably in the intended flight application APL & JPL perform 100% electrical verification at the mission temperature profile extremes. Since little power is dissipated during electrical tests, the device integrity is not compromised.

Visual & Mechanical Inspection

Visual inspection should be performed, on a 100% basis, in accordance to the nearest applicable standard (i.e., military, JEDEC, best commercial practices, etc.). Mechanical inspection should be performed, on a sample basis, in accordance to the same. The intent of these inspections is to ensure device compliance to purchase order requirements.

Radiographic Examination

Radiographic examination (X-ray) should be performed, on a 100% basis, in accordance with MIL-STD-883, Method 2012, "Radiography." APL & JPL recommend and use real-time X-ray to obtain beneficial results. Unlike film, real-time X-ray provides high-resolution images in various planes by rotating the devices inside the chamber. This enables the PEMs user to develop a three-dimensional abstraction of the device internal construction. Performance of X-ray should not be viewed in the context of pass/fail criteria attributed to lot rejection. While individual nonconforming parts should be rejected, the true benefit derived from performing the examination is to gain knowledge regarding overall device construction. -

APPENDIX B – QUALIFICATION TESTS

Destructive Physical Analysis (DPA)

As with radiographic inspection, the purpose of conducting DPA is to build a knowledge base of component construction technology. It is hoped that observations and measurements made during DPA will aid in the establishment of uniform pass/fail criteria associated with C-SAM results (delaminations). When DPA was performed, both APL & JPL followed the guidelines established in MIL-STD-1580, "Destructive Physical Analysis for Electronic, Electromagnetic, and Electromechanical Parts," as it was applicable. Currently both Laboratories utilize three decapsulation methods to remove the epoxy novolac formulation. Depending on what is needed to be investigated, either oxygen plasma etching; wet etching with either red fuming nitric and/or fuming sulfuric acid; and thermo-mechanical means including grinding, heating, and breaking of the plastic encapsulation by force are used. Each method has associated advantages and drawbacks.

C-SAM

Studies have shown that delamination at the mold compound/die interface can be the primary cause of electrical failure during temperature cycling [11]. Mold compound/die delamination has been shown to initiate at the die corners and produce stress-induced passivation damage over a large area of the die as the delamination spreads. After delamination, shear displacement in the delaminated regions causes wirebond degradation. Also, metal corrosion is accelerated in the delamination regions. C-SAM has been shown to be an important tool for the detection of delamination in three dimensions within a package. C-SAM inspection is nondestructive and package damage can be tracked through successive stages of reliability testing.

To further understand delamination phenomena, JPL subjects all samples to C-SAM prior to decapsulation. APL performs C-SAM evaluation for information purposes only. Typically APL selects samples from post-T/C or post-85/85 tests. APL does not use the C-SAM results as a basis for lot rejection.

Radiation Hardness Assurance (RHA)

All parts, commercial and/or military must be evaluated for RHA. When required, total dose evaluation is conducted in accordance with MIL-STD-883, Method 5005, "Qualification

and Quality Conformance Procedures," Group E, or equivalent. Because PEMs are not required to be decapsulated, conducting a total dose test is not a cause for concern. For PEMs, Single Event Effects (SEE) testing can be of great cause for concern. Though three methods for PEM decapsulation have been presented, they are traditionally used for constructional analysis. As such, it is not necessary to maintain device functionality. Achieving device functionality can be a formidable task. It is hoped with the advent of higher energy charged ion accelerators that it will no longer be necessary to decapsulate every PEM to perform SEE testing. In the mean time, the process involves much trial and error.

Temperature Cycling (T/C)

The purpose of performing T/C is to cull potential coefficient of thermal expansion (CTE) mismatch concerns. T/C testing can induce or exacerbate delamination, aiding corrosion by creating pathways for moisture ingress. When T/C testing was performed, the guidelines established in Joint Electron Device Engineering Council (JEDEC) Standard JESD-22-A104, "Temperature Cycling" were followed. After the completion of T/C testing, final electrical measurements at the mission temperature extremes (e.g., cold, room, & hot) should be performed. T/C testing is recommended to be performed only when adequate reliability data can not be obtained from the manufacturer.

Steady-State Temperature Humidity Bias Life Test (85/85)

The purpose behind performing 85/85 testing is to assure that parts can survive in the uncontrolled moisture laden environment prior to launch. Specifically, variances in moisture and temperature during integration, test, transportation and storage of the spacecraft. Once in the vacuum of space, moisture becomes a non-issue; moisture is immediately depleted upon entering the vacuum environment. When 85/85 testing was performed, the guidelines established in JEDEC Standard JESD-22-A101, "Steady-State Temperature Humidity Bias Life Test" were followed. After completion of testing, final electrical measurements at the mission temperature extremes (e.g., cold, room, & hot) should be performed. 85/85 testing is recommended to be performed only when adequate reliability data can not be obtained from the manufacturer.

High Temperature Operating Life (HTOL)

HTOL is concerned with infant mortality and the long-term reliability of devices to withstand temperature extremes. When HTOL was performed, the guidelines established in JEDEC Standard JESD-22-A108, "Bias Life" were followed. Dynamic bias is preferred, but not mandatory. It is recommended that electrical measurements at the mission temperature extremes (e.g., cold, room, & hot) be performed prior to the start and at the completion of the test. In addition, it is also recommended to take electrical measurements, at room temperature, at the 168-hour and 500-hour marks. These additional measurements avoid wasting precious schedule time. Due to the long time period between purchase cycles, the space user can anticipate performing HTOL on every lot of PEMs. However, to reduce testing costs, parts purchased at the same time may be able to be qualified as a family.

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